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Molecularly Imprinted Polymers and Highly Porous Materials in Sensing Applications

John A. Hiltz

Defence R&D Canada – Atlantic

Technical Memorandum
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Abstract

Biological sensing systems or biosensors have several characteristics that make them attractive models for military sensing systems. These include specificity, sensitivity, reproducibility, and the ability to detect a wide range of compounds. However, biosensors have limitations. These include sensitivity to extremes of temperature, pressure, or hydrogen ion concentration (pH), and many are incompatible with organic solvents. In some instances, there is a lack of a suitable biosensing material for a particular analyte, while in others cost and time to develop biosensors are excessive.

Biomimetics or bioinspired approaches to sensors or sensor materials development attempt to reproduce the sensitivity and specificity of biosensors while eliminating or reducing some of their limitations. However, the challenges are in producing extremely pure receptors, incorporating them into a sensor, and in increasing the stability of these receptors. In this Technical Memorandum, several bioinspired approaches to the preparation of materials with applications to sensing systems are reviewed and discussed with respect to their strengths and limitations. Specifically, molecularly imprinted polymers (MIPs), synthetic molecular sieves and high surface area, highly porous polymers based on polysilsesquioxanes are reviewed and their applicability to future defence applications discussed.

Résumé

Les systèmes de détection biologique, ou biocapteurs, possèdent plusieurs propriétés qui en font des modèles intéressants de systèmes de détection militaires. Leurs caractéristiques comprennent la spécificité, la sensibilité de détection, la reproductibilité et la capacité de détecter une vaste gamme de composés. Les biocapteurs présentent toutefois des facteurs limitants, notamment leur sensibilité aux conditions extrêmes de température, de pression et de concentration d'ions hydrogène (pH), et de plus, l'utilisation de bon nombre d'entre eux est incompatible avec des solvants organiques. Dans certains cas, il n'y a pas une quantité suffisante de substance permettant de détecter un analyte biologique particulier et, dans d'autres cas, les coûts et le temps requis pour mettre au point des biocapteurs sont excessifs.

Dans le cadre des travaux de mise au point de capteurs et de matériaux de capteurs, les approches utilisées en biomimétique et celles reposant sur les propriétés des substances biologiques visent à reproduire la sensibilité et la spécificité des biocapteurs tout en réduisant ou éliminant certains de leurs facteurs limitants. Toutefois, les défis majeurs consistent à produire des récepteurs d'une très grande pureté, accroître leur stabilité et les incorporer dans la structure du capteur. Le présent document technique contient un examen détaillé de plusieurs approches qui utilisent les propriétés des substances biologiques pour élaborer des matériaux pouvant être utilisés dans des systèmes de détection, ainsi qu'une discussion portant sur leurs qualités intrinsèques et les facteurs limitants connexes. On y traite plus particulièrement de polymères à empreinte moléculaire (PEM), de tamis moléculaires synthétiques et de polymères très poreux et à surface active élevée, à base de polysilsesquioxanes, et de leurs futures applications dans le domaine de la défense.

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Executive summary

Introduction

Biological sensing systems or biosensors have several characteristics that make them attractive models for military sensing systems. These include specificity, sensitivity, reproducibility, and the ability to detect a wide range of compounds. However, biosensors have limitations. These include sensitivity to extremes of temperature, pressure, or hydrogen ion concentration (pH), and many are incompatible with organic solvents. In some instances, there is a lack of a suitable biosensing material for a particular analyte, while in others cost and time to develop biosensors are excessive.

Biomimetics or bioinspired approaches to sensor or sensor materials development attempt to reproduce the sensitivity and specificity of biosensors while eliminating or reducing some of their limitations. However, the challenges are in producing extremely pure receptors, incorporating them into a sensor, and in increasing the stability of these receptors. In this Technical Memorandum, bioinspired approaches to the preparation of materials with applications to sensing systems are reviewed and discussed with respect to their strengths and limitations. Specifically, molecularly imprinted polymers (MIPs), synthetic molecular sieves and high surface area, highly porous polymers based on polysilsesquioxanes are reviewed.

Results

Molecularly imprinted polymer research is focused on the development of novel materials with sensitivities and selectivities similar to those found in biological systems. This is an area of very active research. A site devoted to MIP research lists 1526 papers and 269 reviews published between 1997 and 2006. MIPs with excellent chemical resistance that are specific for a broad range of compounds have been developed. Challenges to the successful application of these materials to sensing include preparing them in forms other than powders or thin films, coupling them to inexpensive transduction devices and response times.

Synthetic molecular sieves and bridged polysilsesquioxanes are highly porous, high surface area materials. The preparation of porous solids from a range of starting materials has resulted in new materials with unusual properties and purities not found in naturally occurring porous materials such as zeolites. This has the potential to extend their use to sensing applications. Challenges include the synthesis of macroscale structures (fibres, films, beads, and millimeter sized single crystals) with monodisperse porosities, processing these materials into forms or shapes (films, fibres, spheres or macroscale patterned structures), increasing their mechanical and chemical stability, functionalization, understanding defect chemistry and diffusion processes in these compounds, and determining the pore and cage structures in these compounds.

Significance

The threat from chemical and biological agents is a continuing concern. The ability to detect them specifically and with a high degree of sensitive is critical in assessing and controlling the potential for harm. MIPs and highly porous materials, such as synthetic molecular sieves and

polysilsesquioxanes, have the potential to provide specific and sensitive detection for a wide range of compounds. These materials and the technologies arising from or using them have potential to address needs delineated in the Directorate Land Requirements (DLR) Soldier System Roadmap – 2020. Specifically, these materials can address requirements in the Sense Thrust for chemical and biological agent sensing, requirements in the Shield Thrust for filtering and collection materials, and in the Sense Thrust at the Operations level as components of autonomous intelligent systems (AIS).

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Sommaire

Introduction

Les systèmes de détection biologique, ou biocapteurs, possèdent plusieurs propriétés qui en font des modèles intéressants de systèmes de détection militaires. Leurs caractéristiques comprennent la spécificité, la sensibilité de détection, la reproductibilité et la capacité de détecter une vaste gamme de composés. Les biocapteurs présentent toutefois des facteurs limitants, notamment leur sensibilité aux conditions extrêmes de température, de pression et de concentration d'ions hydrogène (pH), et de plus, l'utilisation de bon nombre d'entre eux est incompatible avec des solvants organiques. Dans certains cas, il n'y a pas une quantité suffisante de substance permettant de détecter un analyte biologique particulier et, dans d'autres cas, les coûts et le temps requis pour mettre au point des biocapteurs sont excessifs

Dans le cadre des travaux de mise au point de capteurs et de matériaux de capteurs, les approches utilisées en biomimétique et celles reposant sur les propriétés des substances biologiques visent à reproduire la sensibilité et la spécificité des biocapteurs tout en réduisant ou éliminant certains de leurs facteurs limitants. Toutefois, les défis majeurs consistent à produire des récepteurs d'une très grande pureté, accroître leur stabilité et les incorporer dans la structure du capteur. Le présent document technique contient un examen détaillé d'approches qui utilisent les propriétés des substances biologiques pour élaborer des matériaux pouvant être utilisés dans des systèmes de détection, ainsi qu'une discussion portant sur leurs qualités intrinsèques et les facteurs limitants connexes. On y traite plus particulièrement de polymères à empreinte moléculaire (PEM), de tamis moléculaires synthétiques et de polymères très poreux et à surface active élevée, à base de polysilsesquioxanes.

Résultats

La recherche sur les polymères à empreinte moléculaire (PEM) vise principalement à élaborer de nouveaux matériaux présentant une sensibilité et une sélectivité semblables à celles de structures biologiques. Ce domaine de recherche se caractérise par une activité fébrile. Un site consacré à la recherche sur les PEM fournit en effet une liste de 1526 articles et 269 études de la situation publiés de1997 à 2006. On a déjà élaboré des PEM présentant une excellente résistance chimique et une spécificité pour une vaste gamme de composés. L'utilisation de matériaux de ce type dans le domaine des dispositifs de détection comporte de nombreux défis, notamment leur production sous d'autres formes que des poudres et des couches minces, leur intégration dans la structure des dispositifs de transduction peu coûteux et l'optimisation du temps de réponse.

Les tamis moléculaires synthétiques et les polysilsesquioxanes pontés constituent des matériaux très poreux et à surface active élevée. Les études portant sur la préparation de solides poreux à partir d'une gamme de produits de départ ont permis d'obtenir de nouveaux matériaux de très grande pureté possédant des propriétés exceptionnelles qui ne sont pas observées dans les matériaux poreux naturels tels que les zéolites. Ces résultats pourraient permettre d'étendre leur champ d'application et de les utiliser dans le domaine des détecteurs.

Les défis propres à ce secteur comprennent la synthèse de macrostructures (fibres, pellicules, perles et monocristaux de l'ordre du millimètre) présentant une porosité à distribution monodispersée, leur traitement pour obtenir des produits de formes particulières (pellicules, fibres, particules sphériques ou macrostructures régulières), l'accroissement de leur résistance mécanique et chimique et l'élaboration de processus de fonctionnalisation connexes, ainsi que la réalisation d'études visant à bien comprendre les processus de diffusion et de formation de lacunes dans la composition chimique de ces composés et à déterminer la nature de la structure des pores et de la structure en cage qui les composent.

Portée

La menace associée aux agents chimiques et biologiques constitue un sujet de préoccupation constant. L'évaluation et la réduction des risques possibles de dommage exigent la capacité de détecter ces agents de manière spécifique et avec un haut degré de sensibilité. Les propriétés des PEM et de certains matériaux très poreux, tels que les tamis moléculaires synthétiques et les polysilsesquioxanes, pourraient permettre de les utiliser pour détecter, de manière spécifique et sensible, une vaste gamme de composés. Ces matériaux et les techniques qui les utilisent ou en découlent peuvent éventuellement combler les besoins énoncés dans la Carte routière technologique de l'équipement du soldat – 2020 (*Soldier System Roadmap – 2020*), publiée par la Direction - Besoins en ressources terrestres (DBRT). Les matériaux peuvent particulièrement répondre aux exigences du Volet de la détection, au chapitre de la détection des agents chimiques et biologiques, à celles du Volet de la défense, au chapitre des matériaux de filtration et de captage, ainsi qu'à celles du Volet de la détection, au niveau des opérations, en servant de composants de systèmes intelligents autonomes (SIA).

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1. Introduction

In July 2002 the Technical Cooperation Program (TTCP) sponsored a workshop entitled "Potential Applications of Biotechnical Advances to Materials and Sensing Systems" at the Naval Research Laboratory, Washington, DC. The workshop had two major goals. The first was to evaluate the current state-of-the-art in biotechnology[A] and biological systems and investigate how advances in the understanding of biological systems could be used to enhance sensor, materials and processing technologies. The state-of-the-art review was accomplished through presentations from defence, government and academic scientists. The second goal was to identify potential forms of collaboration possible under TTCP by assessing the application of biosensing, biomaterials, bioelectronics, biomimetics, biostructures and bioinspired approaches to materials and sensing within technical Groups of TTCP. This was to be accomplished by identifying major gaps or weaknesses that exist in TTCP member country programs and by providing recommendations for developing new strategies using advanced materials and biologically based approaches. Biologically based approaches include biomimetics[B] and bioinspired approaches. Bioinspired approaches seek to exploit supramolecular[C] chemistries to build structures at the nanometer scale. Bioinspired materials resemble biogenic materials in form but use substances and structures that are not from nature. To accomplish the second goal, the TTCP MAT Group established an Action Group – MAT AG-13 "Biotechnological Advances to Materials and Sensing Systems".

The aims of MAT AG 13 were to explore potential applications of biotechnology to materials and sensing systems, to identify and explore new approaches with the respective technical groups and to propose collaborative activities. MAT AG 13 developed a way ahead that included the collection and analysis of program information related to biotechnology and its applications in the member countries, the analysis of this information to determine where the member countries were and where they might want to be, the definition of a virtual requirement, and a gap analysis on the basis of this virtual requirement. The aim of the gap analysis was to highlight areas of research and/or development that would be required to realize the virtual requirement. It was felt that these areas would represent opportunities for TTCP collaborative studies.

[A] Biotechnology is defined as "any technique that uses living organisms, or parts of organisms, to make or modify products, improve plants or animals, or to develop micro-organisms for specific uses" (Peter Biggins, Alastair Hutchinson and Douglas Imeson, "Biotechnology for autonomous sensing systems: opportunities and challenges", journal of defence Science, 229, volume 10 (2006)).

[B] Biomimetics are defined as human-made processes, substances, devices, or systems that imitate nature.

[C] Supramolecular chemistry refers to the area of chemistry which focuses on the noncovalent bonding interactions of molecules. Traditional organic synthesis involves the making and breaking of covalent bonds to construct a desired molecule. In contrast, supramolecular chemistry utilizes far weaker and reversible noncovalent interactions, such as hydrogen bonding, metal coordination, hydrophobic forces, van der Waals forces, pi-pi interactions, and/or electrostatic effects to assemble molecules into multimolecular complexes. Important concepts that have been demonstrated by supramolecular chemistry include host-guest chemistry, self-assembly, and molecular recognition. (http://en.wikipedia.org/wiki/Supramolecular_chemistry)

An intelligent remote autonomous sensor (IRAS) system, a concept developed in the UK, was selected as the virtual requirement. There were several reasons for this choice. Defence and security forces have a requirement for improved chemical, biological and radiological sensing systems. In addition, the application of biotechnology, biomimetics and bioinspired approaches show great promise for the development of systems of this type. A schematic of the IRAS concept is shown in Figure 1.

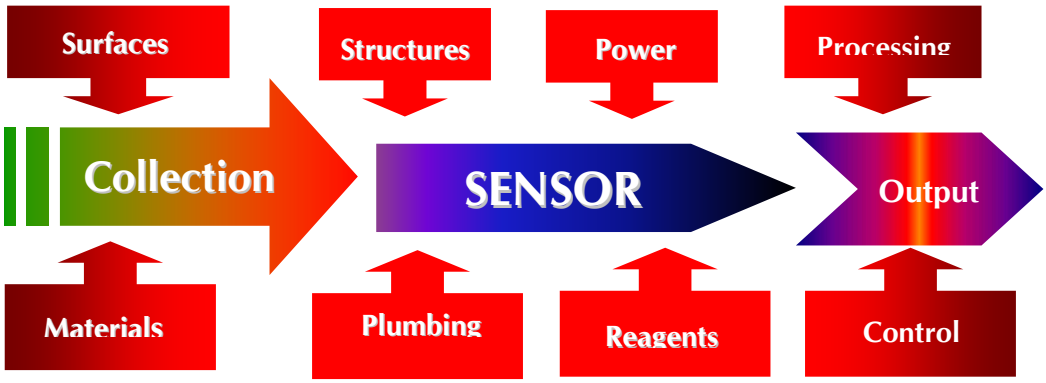

Figure 1. *Schematic of an intelligent remote autonomous sensor (IRAS) system.*

A gap analysis was carried out to determine where biotechnology, biomimetics and bioinspired approaches might have the greatest impact on the components of this sensor system. The analysis indicated that these techniques would have a high impact on sensor surfaces, receptors (encompassing materials and surfaces) and structures, a medium impact on collection and sensor elements (transducers), and a low impact on power sources.

1.1 Biosensors

Biological sensing systems or biosensors have several characteristics that make them attractive models for sensing systems.

The first of these is specificity. Biological sensing systems are based on enzyme/substrate, antibody/antigen or hormone receptor interactions. Enzymes transform a substrate and only that substrate to a unique product and as the enzyme remains unchanged, it is reusable and leads to a sensing system that has an extended lifetime. The specificity of antibody/antigen reactions are based on binding interactions, such as hydrophobic, van der Waals and electrostatic interactions and hydrogen bonding. The surfaces of the antibody and antigen have complimentary shapes with respect to their surface structures and this maximizes affinity

and enhances specificity. Similar binding interactions are responsible for the specificity of hormone receptor reactions.

The second is that biological systems produce very complex molecules and structures in a reproducible way.

The third is biological systems/sensors can detect a wide range of analytes. Biomolecules are nanoscale in size, can be integrated into nanoscaled structures, and are available, that is, they can be produced at any time from natural sources.

However, biosensors have limitations. The first is the stability of biomolecules. Some are sensitive to extremes of temperature, pressure, hydrogen ion concentration (pH), and many are incompatible with organic solvents. In some instances there is a lack of a suitable biosensing material for a particular analyte. Cost and the time to develop processes to produce biosensing systems have also limited the use of biotechnology in some sensing applications.

So in using bioinspired materials or approaches in the development of sensing systems, one would like to keep the strengths of biosensing systems, such as selectivity, sensitivity, and reproducibility, and eliminate some of their limitations, such as environmental sensitivity and cost. Biomimetics or bioinspired approaches attempt to reproduce the sensitivity and specificity of biosensors while eliminating or reducing some of their limitations. However, the challenges are in producing extremely pure receptors, incorporating them into a sensor, and in increasing the stability of these receptors.

1.2 Sensors

The design and operation of a sensor are dependent on a numbers of parameters. These include the nature of the analyte (gas, liquid or solid), the sensitivity of the sensor for the analyte, the selectivity and/or specificity of the sensor for the analyte, whether or not the sensor is to be used more than once, the desired life of the sensor and the environment in which the sensor will be used. These parameters and therefore the function of a sensor are related to the sensor material (surface and structure), signal transduction, and power source used in the fabrication of the sensing device.

The properties of the sensor depend on a number of factors. These include the materials used to prepare it and how they are processed, the area of the sensor surface and/or density of receptor sites, modifications that alter its selectivity, and its connectivity to other sensor elements such as the transduction element. For instance, materials might include polymers, molecularly imprinted polymers, dendrimers, porous silicon, optical fibres, nanoparticles/metallics, aptamers[D] or viral capsids[E]. The morphology, porosity, and material

[D] Aptamers are chemically synthesized (usually short) strands of oligonucleotides (DNA or RNA) that can adopt highly specific three-dimensional conformations. Aptamers are designed to have appropriate binding affinities and specificities towards certain target molecules. (http://en.wikipedia.org/wiki/Aptamer)

[E] Viral Capsid - The outer shell of a virus is called the capsid. It consists of several monomeric subunits made of protein. The capsid serves three main purposes: a) it protects the genetic material of the virus, b) it determines if a cell is suitable for infection and c) it starts the actual infection by

fabrication method all have an effect on the active site density of the material. The sensor specificity is influenced by the homogeneity of the receptor sites. Speed of response will depend on the time it takes for the analyte to reach the receptors, and the amount of analyte that must reach the receptor to affect a change in the transducer. The transducer element may be optical, electrochemical, or gravimetric and this will influence sensor design.

The environment where the sensor will be used will also impact its design. In certain environments, degradation and fouling will limit sensor lifetime. The preparation of self-cleaning and regenerative sensor surfaces would extend the useful life of a sensor element. This could be accomplished through the release of antifouling compounds by the sensor material. Conversely, one might wish to incorporate biodegradability for environmental reasons.

In this Technical Memorandum, three bioinspired/biomimetics approaches to the preparation of materials with applications to sensing systems are reviewed and discussed with respect to their strengths and limitations. The first approach involves molecular imprinting of polymers. Molecularly imprinted polymer research is focused on the development of novel materials with sensitivities and selectivities similar to those found in biological systems. The second and third involve the development of synthetic molecular sieves and bridged polysilsesquioxanes. These materials are highly porous, high surface area materials that have applications in sample collection and separation and the potential to be used as sensor surface materials with controllable selectivity.

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attaching and "opening" the target cell and injecting the genetic material of the virus into the cell. (http://en.wikipedia.org/wiki/Viral Capsid)

2. Molecularly Imprinted Polymers (MIPs)

Molecular imprinting is a bioinspired approach to preparing synthetic polymers with selective recognition properties for particular analytes. The goal of molecular imprinting is to prepare polymer-based substrates with selectivities similar to those found for naturally occurring systems (1).

2.1 The Literature

A substantial literature on MIPs exists. For instance, a site devoted to MIP research (2) lists 1526 papers and 269 reviews published between 1997 and 2006. Both the papers and reviews deal with a broad range of topics and a survey of the reviews published in the last fours years is indicative of activity in the area. Review topics include the use of MIPs in catalysis (3-7), as stationary phases in chromatographic separations (8-11), in solid phase extractions (12-18), in drug delivery (20-22), and as components of sensors (23-32). The use of combinatorial methods to develop MIPS (33-35) and characterization and synthesis of MIPs (36-39) have also been reviewed. In addition, a number of reviews dealing with MIPs in a more general sense have been published (40-45).

2.2 Preparation

The classic approach to the preparation of molecularly imprinted polymers involves the copolymerization of functional and cross-linking monomers in the presence of a target analyte (the imprint molecule). The polymerization is often carried out in a solvent (porogen). The solvent acts not only to dissolve the monomers and imprint molecules but also mediates interactions between the functional groups and the imprint molecule, determines the timing of phase separation during the polymerization which affects morphology, and generates a porous structure in the MIP (35). The porous structure facilitates the extraction of imprint molecules and subsequent ingress of the analyte to the imprinted sites.

The imprinting of the polymer depends on the interaction of the target molecule with the functional monomer. This interaction can take place in one of two ways. In the first, a complex between the imprint molecule and the functional monomer is formed based on weak intermolecular interactions (ionic or hydrophobic interactions, hydrogen bonding, and metal coordinations) prior to polymerization. This approach is shown schematically in Figure 2. Mosbach and coworkers pioneered the development of this approach (46). Following polymerization, the MIP is washed with solvent to remove the imprint molecule. In the second, covalent bonds are formed between the functional monomer and the imprinted molecule to yield a polymerizable derivative of the imprinted molecule that is then polymerized. Wulff and colleagues pioneered the development of this approach (47). With this synthetic approach, covalent bonds must be broken prior to removal of the imprint molecule.

Each approach has its advantages. The covalent imprinting approach should yield a larger and more homogenous population of binding sites than the noncovalent approach for a given amount of imprint molecule. However, the noncovalent approach is more flexible with respect to the choice of functional monomers and possible target molecules.

Molecularly imprinted polymers have been prepared in a number of physical forms. These include powders prepared by mechanical grinding of a block of imprinted polymer, particles prepared in the form of spherical beads in two phase systems (48-50); aggregates of spherical particles using a dispersion polymerization approach (51), and uniform microspheres from dilute dispersion polymerization systems (52). MIPs have also been prepared as imprinted membranes by precipitation of linear polymers from solution in the presence of the analyte (53) and by casting an imprinted polymer into the pores of a support membrane (54).

The templating of self-assembled monolayers can be thought of as two-dimensional molecular imprinting. For instance, when a self assembled monolayer of alkane thiols is formed on a gold surface in the presence of another molecule, that molecule leaves holes in the monolayer that form a binding site for a guest molecule (55-57).

Molecularly imprinted polymers with excellent affinity and specificity for a large range of analytes have been synthesized. Analytes include small organic molecules, pharmaceuticals, pesticides, amino acids and peptides, nucleotide bases, steroids and sugars. Analytes with larger structures present a more difficult challenge.

2.2.1 Materials

MIPs have been prepared from a wide range of polymers and with a wide range of imprinted molecules. These include a number of acrylic acid and acrylate ester-based monomers including methacrylic acid/2-(trifluoromethyl)acrylic acid (58), methyl methacrylate/4-vinylpyridine/N-vinyl-α-pyrrolidone and methacrylic acid/2-(trifluoromethyl)acrylic acid (59), ethylene glycol dimethacrylate/methacrylic acid (60), acrylamide functionalized nitrilotriacetic acid ligand with Ni prepolymer/N,N'-ethylenebis(acrylamide) (61,62), and tripropyleneglycol diacrylate/diacryolyl-2,6-diaminopyridine and dodecylthymine (63). MIPs have also been prepared from solution cast thermoplastics (Nylon) (64), as sol-gels from 3-[N,N-bis(9-anthrylmethyl)amino]propyltriethoxysilane, tetraethoxysilane, and phenyltrimethoxysilane (65), and hydrogels from poly(allylamine hydrochloride)/epichlorohydrin (66,67).

2.2.2 MIPs in Sensors

In a biosensor, when the analyte binds to the recognition element a response is generated. In biomimetic or bioinspired sensors involving MIPs, the MIPs act as the equivalent of the recognition elements in biosensors. Takeuchi et al. (68) indicate there are three ways to achieve signaling in MIP systems: detection of signals due to the inherent properties of the target molecules, detection of labeled molecules, and detection of changing properties of the polymer resulting from binding the target molecules. Detection of the signal requires a transduction element (transducer). These elements can be optical, piezoelectric or electrochemical in form.

Piletsky and Turner (69) indicate that there are three critical issues to the design of MIP based sensors. These are the development of sensitive transducers capable of monitoring the

binding process and transforming it into a signal, the development of MIPs capable of interacting with the analyte under the desired conditions and with the required affinity and specificity, and the integration of the MIP with the transducer.

A number of transducers have been coupled with MIPs to form sensors. Transducers based on ellipsometry, electrochemical changes, surface acoustic wave (SAW) frequency change, weight change (quartz crystal microbalances (QCM)), and surface plasmon resonance frequency change have been used to measure analyte concentration (45) with varying degrees of success (70).

Electrochemical sensing has a number of advantages over other techniques including good limits of detection, low cost, easy miniaturization and the potential for automation (71). Macroporous methacrylate, acrylate, acrylamide, and vinyl-based MIPs have exhibited excellent selectivity but are difficult to combine with transduction elements for electrochemical sensing. These polymers are non-conducting and therefore cannot be used as the electrode in electrochemical sensors (72). As a result of this they must be coupled to a transduction element. This has proven to be difficult. Materials incorporating a MIP and a conducting polymer show promise for use in sensors as they combine the selectivity of the MIP with simple signal transduction (73).

2.2.3 Challenges

There are a number of challenges to the use of MIPs as recognition elements in sensors. Some, such as coupling of the MIP to a suitable transduction element, have been mentioned in the preceding sections. The response time of sensors is an important parameter. If the analyte has to diffuse into the MIP, this can limit the physical form of the MIP (thickness of a film or size of a powder). The physical form of the MIP will also influence the reversibility of the binding process and ultimately the reusability of the sensor. That is, questions such as *how long will it take to remove the analyte*? and *how complete will the removal process be?* must be considered. A major challenge to the use of MIPs for sensing applications is to prepare them in forms other than powders or thin films. The ability to prepare MIPs with two dimensional (2-D) and three-dimensional (3-D) structures is still in its developmental stages. A number of techniques including lithography, microcontact printing, microstereolithography, and 2-photon 3-D lithography have been used to produce the type of 2-D and 3-D structures required for sensor applications. A microstereolithography technique has been described in the literature (74) for the preparation of 2-D and 3-D structures. Localized photopolymerization with a focused laser beam was used to build the MIP structure.

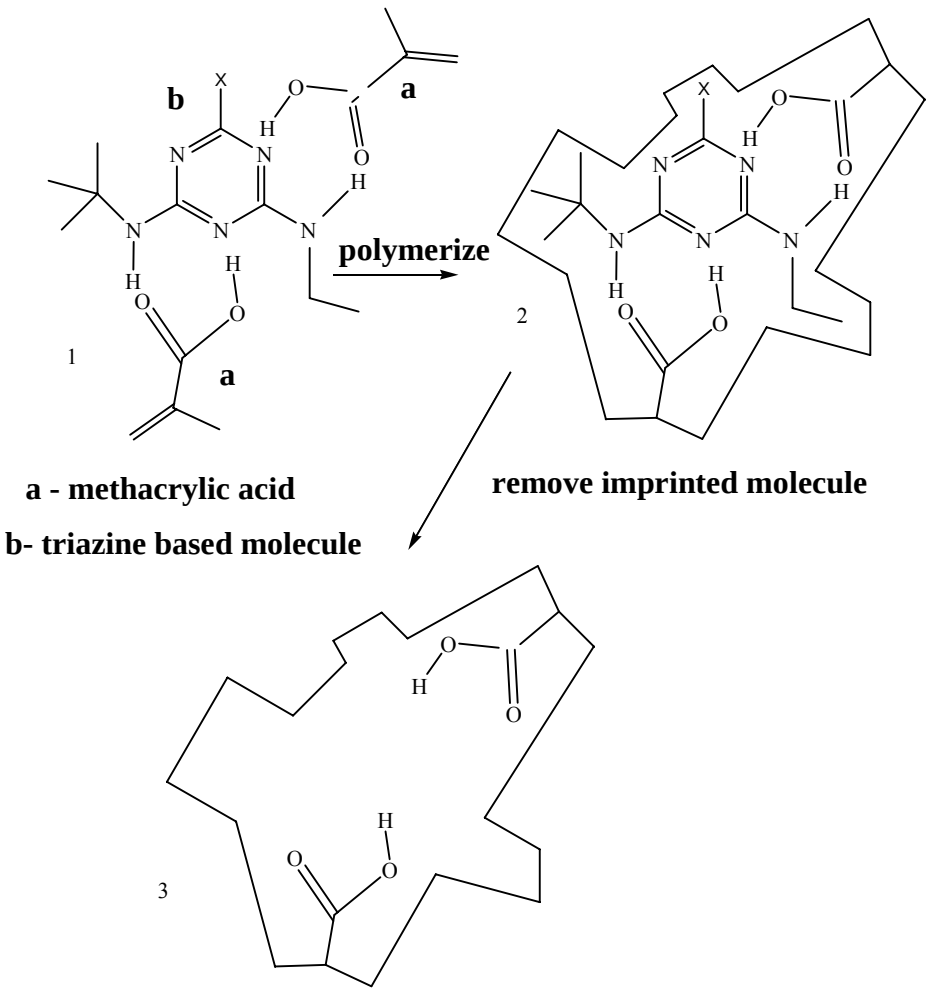


Figure 2. Preparation of a molecularly imprinted polymer.

3. High Surface Area/Highly Porous Materials

These materials can be thought of as synthetic analogues of naturally occurring mineral or biological materials.

Nature produces materials with hierarchical structures with order on the nanometer (atom and molecule) level through the micrometer and onto the millimeter level. Porous materials research aims to control the size, shape and uniformity of the pores and the atoms and molecules that define them (75). Stucky defines high surface area porous materials technology as follows. "High surface area materials (300 – 2000 m^2/g) technology is directed at creation of inexpensive low bulk volume/area media for applications that require rapid and responsive sampling, selective separations, catalytic processing, enhanced chemical reactivity, or 3-D packaging of supported or entrained nanoscopic structured species. The high surface area of these materials provides a means to achieve detection sensitivities in the ppb range or to rapidly sample and chemically process large volumes of reactants." (76)

Fractional void space in porous materials is in the range of 0.9 with pore volumes ranging from 0.6 cm^3/g to 2.7 cm^3/g. The ability to create three dimensional patterning and periodicity results in the optimum surface area/volume control, useful access space, and control of structure and properties at the nanoscale level. The ability to control pore size at the Angstrom level (10^{-10} m) results in materials with selectivities for separation or catalytic processes that are several orders of magnitude better than previously possible.

One of the potential applications for this technology is in chemical sensing using films, spheres or fibres (77, 78). There are a number of control parameters required for this type of application and they are similar to those of enzymes in biocatalysts. Key variables include: molecular recognition parameters, transition state lifetimes, sorption and desorption rates, the ability to functionalize the surface, chemical and mechanical stability of materials, defined defect structure, and interface chemistry from both a synthesis and composite property perspective.

3.1 Synthetic Molecular Sieves

3.1.1 Synthesis – Critical Parameters

Zeolites are an example of porous minerals. Zeolites are hydrated alumino-silicate minerals with an open, porous structure and are members of the molecular sieve family. Because of their molecular-sized and regular pore structures, these minerals can separate molecules on the basis of size. Some typical zeolite structures are shown in Figure 3 (79).

The preparation of porous solids from a range of starting materials has resulted in new materials with unusual properties and purities not found in naturally occurring porous materials such as zeolites. The synthesis of new porous materials has extended applications beyond those as catalysts and absorbents. One of these is in sensing applications. An

excellent review of the synthesis and applications of molecular sieve layers and membranes and is found in Reference 80.

Three approaches have been used to prepare porous material, for example, zeolites, as layers and films. The first is to deposit or embed the preformed crystals on a suitable substrate. The second involves transport of colloidal or polymeric, amorphous aluminosilicates to the surface of the substrate. This results in supersaturated conditions that promote nucleation and growth under hydrothermal conditions at the substrate surface. The third involves direct nucleation of the substrate surface from solution or a gel film, followed by growth. However, if control of the kinetics governing the interfacial and assembly processes can be realized, then the preparation of materials with a broad range of properties (controlled surface area, morphology, void space, pore volume and functionality) will be possible.

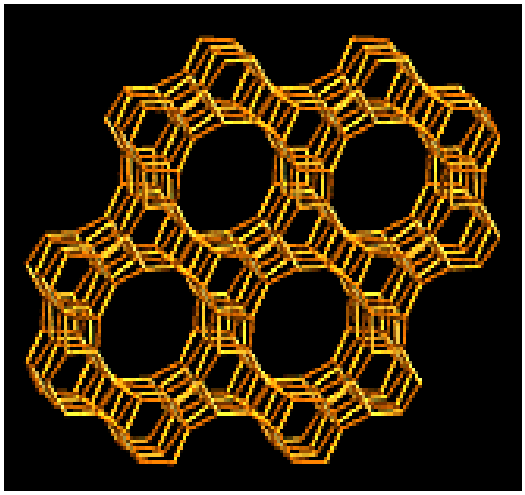
3.1.2 Challenges

A form of molecular imprinting defines the topology of high surface area materials at the nanostructure level. The imprinting can involve single molecules or organized arrays of molecules. The actual forms of the materials created depend on several factors. These include the relative kinetics and thermodynamics of the polymerization of the molecules that make up the surface, the interface interactions between these molecules and those responsible for the creation of the high surface area and surface nanostructure, and the intramolecular interactions of these molecules.

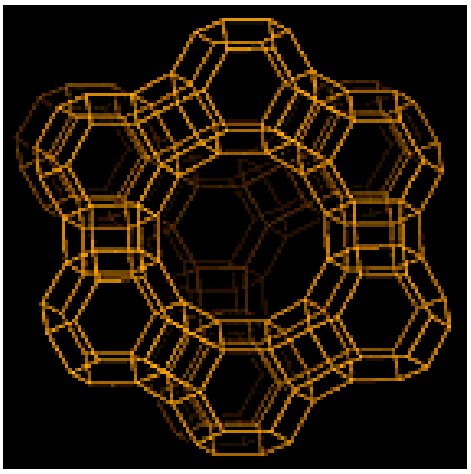
There has been limited success with the synthesis of high surface area macroscale structures (fibres, films, beads, and millimeter sized single crystals) with monodisperse porosities. Processing of high surface area materials into forms or shapes (films, fibres, spheres or macroscale patterned structures) that can be used for a particular application is a challenge. A goal in this area is to design structures based on nanoscale molecular assembly that incorporate control of structure and properties on a space and time basis.

Progress in generating monodisperse, high surface area materials containing 3-D periodic arrays of pores and cages above the 10 nm region has been slow. Attempts to prepare materials that bridge the nanoscale ($<10^{-7}$m) to mesoscale (up to 10^{-3}m to 10^{-2}m) dimensions has resulted in loss of short range order at the nanoscale level.

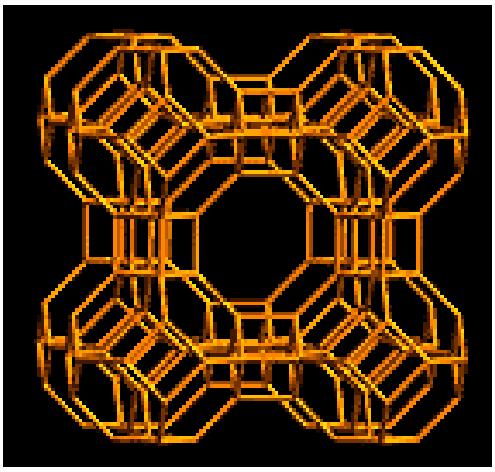
There are a number of other parameters that must be addressed to enable the use of high surface area materials. These include the mechanical and chemical stability of high surface area, large pore size materials, functionalization, defect chemistry, diffusion processes and the determination of the pore and cage structures in these compounds.



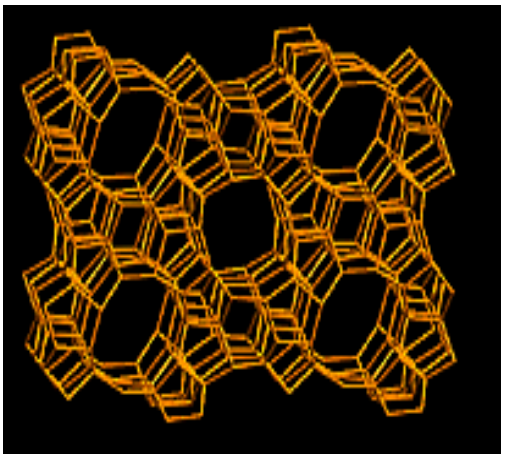
Zeolite AFI - Tetrapropylammonium Fluoride AlPO-5



Zeolite FAU - Faujasite



Zeolite LTA - Linde Type A



Zeolite MFI - Tetrapropylammonium ZSM-5

Figure 3. Some typical zeolite structure (Reference 79).

3.2 Bridged Polysilsesquioxanes

3.2.1 Preparation

Shea and Loy (81) define bridged polysilsesquioxanes as hybrid organic-inorganic materials prepared by sol-gel processing of monomers containing an organic bridging group and two or

more trifunctional trihalosilyl or trialkoxysilyl groups. Typical trialkoxysilyl monomers are shown in Figure 4. The organic bridging portion of the monomers can vary significantly and includes rigid arylene and acetylene groups, flexible alkylene groups containing up to 14 methylene groups, and functionalized amines, ethers, sulfides, and carbonates. Hydrolysis of the monomers and subsequent condensation steps lead to the formation of polysilsesquioxanes. By varying the nature of the organic bridging group, the bulk properties of the resulting polymer, such as porosity, thermal stability, chemical resistance, and hydrophobicity, can be changed.

Normal drying of polysilsesquioxanes results in xerogels. These amorphous low-density materials can lose as much as 95% of their volume on drying. The shrinkage can lead to the collapse of pores and result in a non-porous material (82). However, most bridged polysilsesquioxane xerogels remain porous with surface areas between $200m^2/g$ and $1200m^2/g$.

Supercritical drying of polysilsesquioxanes results in the formation of aerogels. These very low density materials have been prepared in two ways. The first method involves the replacement of the solvent used in the sol gel preparation with supercritical carbon dioxide (CO_2) (83). The supercritical CO_2 is then slowly vented. In the second method the monomers are polymerized with formic acid in the presence of supercritical CO_2 followed by the slow venting of CO_2 (84). The use of supercritical fluids prevents the collapse of the resulting porous polysilsesquioxane structure. Surfactant templating techniques have also been used to prepare bridged polysilsesquioxanes (85). This results in the formation of mesoporous (pore width 2nm to 50nm) materials.

3.2.2 Surface Area and Porosity

The organic bridging groups affect the size, shape, geometry and functionality of the polysilsesquioxane monomers and therefore bulk properties, such as porosity, of the polymer (81). In amorphous bridged polysilsesquioxanes, the compliance of the network is an important contributing factor to porosity. The compliance depends on the degree of condensation of the silicon and the flexibility of the bridging group. Sol gels prepared under acidic conditions tend to have lower degrees of condensation than those with basic catalysts. For instance, polysilsesquioxanes prepared from monomers with flexible bridging groups, such as long chain alkylenes, under acidic conditions are susceptible to collapse and can result in non-porous xerogels or thin films.

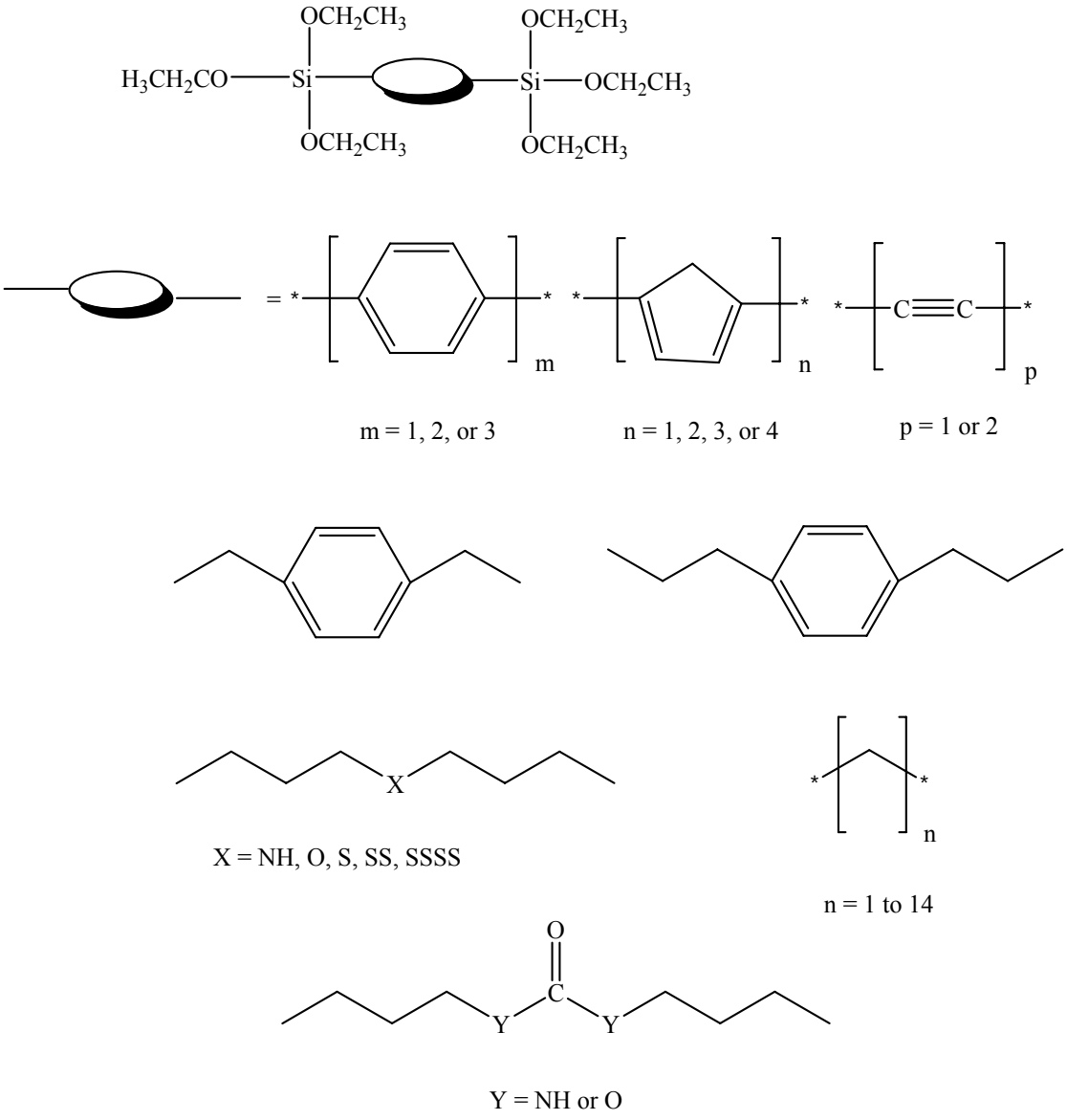


Figure 4. Some monomeric trialkoxysilyl starting materials used in the preparation of bridged polysilsesquioxanes.

Less compliant networks retain their porosity on drying. Materials with less compliant networks are prepared using basic catalysts and from monomers with less flexible bridging groups. These materials can have surface areas up to 1800m^2/g. Micropores (widths less than 2nm) make a significant contribution to the surface area. Mesoporous xerogels (pore widths from 2nm to 50nm) can be prepared using a basic catalyst and alkylene bridging groups containing up to 10 carbons.

The organic bridging group can also be used as a template to create porosity. The organic bridging group occupies space in the polysilsesquioxane until burned away, oxidized, hydrolyzed or changed by chemical rearrangements. This process leaves pores that are roughly of the same size and shape as the bridging group. Thermolysis of non porous xerogels has produced porous silica gels, while the oxidation of porous xerogels resulted in gels with larger pore sizes. This technique has been used to template porosity in silica membranes (86).

Chemical reactions can also be used to modify, cleave, or remove portions of bridging groups in polysilsesquioxanes. For instance, hydrolysis of carbamate linkages in the bridging group has been used to prepare aminoalkyl functionalized polysilsesquioxanes (87).

The polysilsesquioxanes exhibit excellent thermal stability. The literature indicates that phenylene bridged polysilsesquioxanes are stable to 500^{o}C (88) while alkylene bridged polysilsesquioxanes are stable to over 400^{o}C (89).

3.2.3 Applications

The high surface area and chemical functionality of bridged polysilsesquioxanes makes them candidate materials for separation media, as pore templates and structural materials for membrane materials, as catalyst supports, and as metal and organic absorbents.

4. Potential

4.1 Military Applications

Major advances in the understanding of biological systems, and therefore how one might exploit them, continue. Organisms have evolved the ability to sense many stimuli (such as light, sound, heat and pressure as examples), along with physical structures and processing systems in order to enhance their survivability in the environment. Clearly the mechanisms underpinning these biological sensing functions, material structures and processing systems have application in a wide range of defence sensor technologies, structural designs, power sources and microsystems. Biotechnology will hence have a very wide impact on many types of defence equipment, with the potential to create new disruptive technologies.

A recent TTCP report (90) lists three areas relevant to military applications that could exploit biotechnological advances. These areas are human performance enhancement, biological sensors, and biomaterials and nanofabrication.

Human performance enhancement research is focused on improving perception, information processing, decision-making, and task execution capabilities using miniature sensing and data fusion systems. As one example, low power systems could detect physiological changes in real time and lead to adaptations in cardiovascular or neurological functioning. Biotechnology is also being used to develop information display and control for improved decision-making and reaction times.

Biological sensors have perhaps benefited the most from biotechnology through advances in optics, electronics, microfabrication technology, and molecular biochemistry. Receptor elements and transducers being researched include gene probes, monoclonal and genetically engineered antibodies and other receptors, high-precision polymer moulding, molecularly imprinted polymers, polymer liquid crystals, chemiluminescence, neuronal and protein DNA patterning, combinatorial chemistry, monolithic ultraviolet/visible/infrared laser light-emitting and -detecting surfaces, microelectromechanical systems (MEMS), charge coupled devices (CCDs), and neural networks. Sensors are being fielded that are more sensitive, with miniaturized components and lower energy requirements. Sensor integration and connectivity with operational systems could allow military units to respond much as the sensory nervous system does in the body.

Biomaterials and nanofabrication represents the intersection of biological and nanotechnology. By achieving miniaturization at the nanometer-scale level, it is possible to develop high-density information storage, retrieval, and processing capabilities. Biomaterial-based circuit and switching devices on the nanometer scale will enable rapid and accurate responses to changing requirements for military applications. The rapid progress in biochemistry and molecular biology has already provided industry with many new classes of materials. These include structural materials (silks and bioceramics); sensing materials (MIPs, synthetic zeolites), electron/photon conductive polymers; ion gating molecules including

bioreceptors (adhesives from barnacles that can function on wet surfaces); and lubricants that are biocompatible.

4.2 Pertinence to the Integrated Soldier System Project Roadmap – 2020

It may be more useful to consider how MIPs and highly porous materials, such as synthetic zeolites and polysilsesquioxanes, might impact on future defence requirements.

The Soldier System Roadmap Workshop, sponsored by Directorate Land Requirements (DLR) in November 2005, reviewed 2100 technologies that might be integrated into future designs for soldier systems and attempted to assign technology readiness levels and maturity dates to each technology. The technologies were assigned to one of five Operation Levels; Soldier System, Tactical, Operational, Strategic, and Strategic Implementation. Each of the technologies was then assigned to one of five Thrust areas; Command, Sense, Act, Shield, and Sustain, within each Operational Level. The resulting document is called the Soldier System Roadmap – 2020.

The Soldier System Roadmap – 2020 document was reviewed to determine where the materials discussed in this Memorandum might impact future Army requirements. MIPs and highly porous materials with defined pore size(s) will find applications in biological and chemical sensors as sensor components (specific interaction with analyte) and as collection and separation elements for sensing systems. These materials are covered in sections 1.2.1.4 Biological and 1.2.1.5 Chemical in the Sense Thrust of the Soldier Systems Operation Level. Synthetic zeolites and materials such as polysilsesquioxanes may find applications as separation, filtration, or absorption media (1.4.7.1.1 Materials and 1.4.7.2.2 Filter in the Shield Thrust of the Soldier System Operational Level). These materials may also find applications as subcomponents of sensing systems such as those covered under section 2.2.1.3 Technologies and its subsections in the Sense Thrust Tactical Level.

The IRAS (intelligent remote autonomous sensing) system referred to in the Introduction is conceptually similar to the Autonomous Intelligent Systems (AIS) in section 3.2.1 Fully Autonomous Sensor Network in the Sense Thrust Operational Level (section 3.2). One can envision MIPs, synthetic zeolites and highly porous materials such as polysilsesquioxanes as components of sensors used in such systems.

5. Conclusions

The question is: how do MIPs, synthetic zeolites and polysilsesquioxanes act as enablers for sensing, filtering, and collection applications? The driving force for research in this area is the development of materials that address the shortcoming of biological systems. These include sensitivities to environmental factors such as temperature, humidity, pH, and solvents that can limit shelf life or require the sensor be stored in a controlled environment. A synthetic approach can also lead to sensor elements or sensor subcomponents that are not available from biological or natural systems.

The incorporation of synthetic materials, such as molecularly imprinted polymers, into sensing systems remains a challenge. Many of the polymers used in MIPs are non conductive and this makes coupling of the sensing component with an electrochemical based transducer difficult. However, the development of MIPs/conducting polymer blends or interpenetrating networks has the potential to overcome this limitation.

Synthetic molecular sieves and porous materials based on bridged polysilsesquioxanes have applications to the sample collection and separation aspects of sensors. Pore size control and subsequently the development highly porous materials with controlled surface chemistry remains a challenge. As was noted for MIPs, coupling of a highly porous material with controlled surface chemistry, and therefore selectivity, to a transduction element will be a challenge.

6. References

1. D. Kris, O. Ramstrom, and K. Mosbach, “Molecular Imprinting – New Possibilities for Sensor Technology”, Analytical Chemistry, 345A – 349A (1997).

2. http://www.smi.tu-berlin.de/Base/Database.htm

3. C.Alexander, L. Davidson and W. Hayes, “Imprinted polymers: artificial molecular recognition materials with applications in synthesis and catalysis”, Tetrahedron 59, 2025-2057 (2003).

4. J. J. Becker and M.R. Gagne, “Exploiting the synergy between coordination chemistry and molecular imprinting in the quest for new catalysts”, Accounts Chem. Res., 37, 798-804 (2004).

5. A.Corma, “Attempts to fill the gap between enzymatic, homogeneous, and heterogeneous catalysis”, Catalysis Reviews-Science and Engineering 46(3-4),369-417 (2004)

6. PO. Mastrorilli and C.F. Nobile, “Supported catalysts from polymerizable transition metal complexes”, Coordination Chemistry reviews”, 248(3-4), 377-395 (2004).

7. M. Tada. and Y. Iwasawa, “Chemical design and in situ characterization of active surfaces for selective catalysis”, Annual Review of Materials Research 35, 397-426 (2005).

8. J. Bojarski, H.Y. Aboul-Enein and A. Ghanem, “What's new in chromatographic enantioseparations” Curr. Anal. Chem., 1, 59-77 (2005).

9. T. Y. Guo, L. Y. Zhang, G. J. Hao, M. D. Song and B. H. Zhang, “Molecular imprinting polymers for chiral separation of amino acid derivatives”, Progress in Chemistry 16(4), 638-642 (2004).

10. H. Y. Liu, , K. H. Row and G. L. Yan, “Monolithic molecularly imprinted columns for chromatographic separation”, Chromatographia, 61,429-432 (2005).

11. Y. Liu, A. W. Lantz and D. W. Armstrong, “High efficiency liquid and super-/subcritical fluid-based enantiomeric separations: An overview”, Journal of Liquid Chromatography & Related Technologies, 27(7-9), 1121-1178 (2004).

12. E. Caro, R. M. Marce, F. Borrull, P. A. G. Cormack and D. C. Sherrington, “Application of molecularly imprinted polymers to solid-phase extraction of compounds from environmental and biological samples”, Trends Anal. Chem., 25, 143-154 (2006).

13. F. Chapuis, V. Pichon and M. C. Hennion, “Preconcentration by solid phase extraction: Principles and applications in the environmental and petroleum industries”, Oil & Gas Science and Technology-Revue de L Institut Francais du Petrole, 60, 899-912 (2005).

14. F. Chapuis, V. Pichon and M. C. Hennion, “Molecularly imprinted polymers: Developments and applications of new selective solid-phase extraction materials”, LC-GC Europe, 17(7), 408-417 (2004).

15. S. G. Dmitrienko, V. V. Irkha, A. Y. Kuznetsova and Y. A. Zolotov, “Use of molecular imprinted polymers for the separation and preconcentration of organic compounds”, J. Anal. Chem., 59, 808-817 (2004).

16. J. Haginaka, “Molecularly imprinted polymers for solid-phase extraction”, Anal. Bioanal. Chem., 379(3), 332-334 (2004).

17. J. Haginaka, “Selectivity of affinity media in solid-phase extraction of analytes”, Trends Anal. Chem., 24, 407-415 (2005).

18. S. G. Hu, L. Li and X. W. He, “Molecularly imprinted polymers: A new kind of sorbent with high selectivity in solid phase extraction”, Progress in Chemistry, 17, 531-543 (2005).

19. W. M. Mullett and J. Pawliszyn, “The development of selective and biocompatible coatings for solid phase microextraction”, J. Sep. Sci., 26, 251-260 (2003).

20. D Cunliffe, A. Kirby and C. Alexander, “Molecularly imprinted drug delivery systems”, Adv. Drug Delivery Rev., 57, 1836-1853 (2005).

21. J. Z. Hilt and M.E. Byrne, “Configurational biomimesis in drug delivery: molecular imprinting of biologically significant molecules”, Advanced Drug Delivery Reviews, 56, 1599-1620 (2004).

22. D. L. Rathbone, “Molecularly imprinted polymers in the drug discovery process”, Adv. Drug Delivery Rev., 57, 1854-1874 (2005).

23. F. L. Dickert, P. A. Lieberzeit and O. Hoyden, “Chemical sensors through molecular imprinting”, Nachr. Chem., 51, 1139-1143 (2003).

24. F. L. Dickert, P. A. Lieberzeit, O. Hayden, S. Gazda-Miarecka, K. Halikias, K. J. Mann and C. Palfinger, “Chemical sensors - from molecules, complex mixtures to cells - supramolecular imprinting strategies”, Sensors, 3, 381-392 (2003).

25. F. L. Dickert, P. Lieberzeit and O. Hayden, “Sensor strategies for microorganism detection - from physical principles to imprinting procedures”, Anal. Bioanal. Chem., 377, 540-549 (2003).

26. O. Y. F. Henry, D. C. Cullen and S. A. Piletsky, “Optical interrogation of molecularly imprinted polymers and development of MIP sensors: a review”, Anal. Bioanal. Chem., 382, 947-956 (2005).

27. A. L. Hillberg, K. R. Brain and C. J. Allender, “Molecular imprinted polymer sensors: Implications for therapeutics”, Adv. Drug Delivery Rev., 57, 1875-1889 (2005).

28. L. M Kindschy and E. C. Alocilja, “A review of molecularly imprinted polymers for biosensor development for food and agricultural applications”, Transactions of the ASAE, 47, 1375-1382 (2004).

29. S. Shinkai and M. Takeuchi, “Molecular design of synthetic receptors with dynamic, imprinting, and allosteric functions”, Biosensors & Bioelectronics, 20(6), 1250-1259 (2004).

30. M. Trojanowicz. and M. Wcislo, “Electrochemical and piezoelectric enantioselective sensors and biosensors”, Analytical Letters, 38, 523-547 (2005).

31. L. Ye and K. Haupt, “Molecularly imprinted polymers as antibody and receptor mimics for assays, sensors and drug discovery”, Anal. Bioanal. Chem., 378(8), 1887-1897 (2004).

32. B. Adhikari and S. Majumdar, “Polymers in sensor applications”, Progress in Polymer Science, 29(7), 699-766 (2004).

33. D. Baltra. and K. J. Shea, “Combinatorial methods in molecular imprinting”, Curr. Opin. Chem. Bio., 7, 434-442 (2003).

34. F. Lanza and B. Sellergren, “Molecularly imprinted polymers via high-throughput and combinatorial techniques”, Macromol. Rapid Commun., 25, 59-68 (2004).

35. R. A. Potyrailo, “Polymeric sensor materials: Toward an alliance of combinatiorial and rational design tools?”, Angew. Chem., Int. Ed., 45, 702-723 (2006).

36. K. Karim, F. Breton, R. Rouillon, E. V. Piletska, A. Guerreiro, I. Chianella and S. A. Piletsky, “How to find effective functional monomers for effective molecularly imprinted polymers?”, Adv. Drug Delivery Rev., 57, 1795-1808 (2005).

37. A. G. Mayes and M. J. Whitcombe, “Synthetic strategies for the generation of molecularly imprinted organic polymers”, Adv. Drug Delivery Rev., 57, 1742-1778 (2005).

38. D. A. Spivak, “Optimization, evaluation, and characterization of molecularly imprinted polymers”, Adv. Drug Delivery Rev., 57, 1779-1794 (2005).

39. P. A. G. Cormack and A. Z. Elorza, “Molecularly imprinted polymers: synthesis and characterisation”, J. Chromatogr. B, 804(1), 173-182 (2004).

40. D. Cunliffe, S. Pennadam and C. Alexander, “Synthetic and biological polymers-merging the interface”, Eur. Polym. J., 40, 5-25 (2004).

41. A. J. Hall, M. Emgenbroich and B. Sellergren, “Imprinted Polymers” Topics in Current Chemistry, 249, 317-349 (2005).

42. K. Haupt, “Imprinted polymers-Tailor-made mimics of antibodies and receptors”, Chem. Commun., 2, 171-178 (2003).

43. K. Haupt, “Molecularly imprinted polymers: The next generation”, Anal. Chem., 75:376A-383A (2003).

44. V. B. Kandimalla and H. X. Ju, “Molecular imprinting: a dynamic technique for diverse applications in analytical chemistry”, Anal. Bioanal. Chem., 380, 587-605 (2004).

45. J.-D. Marty and M. Mauzac, “Molecular Imprinting: State of the Art and Perspectives”, Adv. Polym. Sci., 172, 1-35 (2005).

46. K. Mosbach and O. Ranstrom, O. Bio/Technology, 14, 163 (1996).

47. G. Wulff, Angew. Chem. Int. Ed. Engl., 34, 1812 (1995).

48. K. Hosoya, K. Yoshihako, Y. Shirasu, K. Kimata, and J. Haginaka, J. Chromatogr., 728, 139 (1996)

49. M. A. Vorderbruggen, K. Wu, C. M. Breneman, Chem. Mater., 8, 1106 (1996).

50. A. G. Mayes and K. Mosbach, Analyst, 68, 3769 (1996).

51. B. Sellergren, J. Chromatogr., 673, 133 (1994).

52. L. Ye, P. A. G. Cormack, and K. Mosbach, Anal. Commun., 36, 35, (1999).

53. H. Y. Wang, T. Kobayashi, and N. Fujii, Langmuir, 12, 4850 (1996).

54. J.-M. Hong, P. E. Anderson, J. Qian, and C. E. Martin, Chem. Mater., 10, 1029 (1998).

55. M. Lahav, E. Katz, A. Doron, F. Patolsky, and I. Willner, J. Am. Chem. Soc., 121, 862 (1999).

56. S. A. Piletsky, E. V. Piletskaya, T.A. Sergeyeva, T. L. Panasyuk, and A. V. El’skaya, Ses. Actuators B, 60, 216 (1999).

57. V. M. Mirsky, T. Hirsch, S. A. Piletsky, O. S. Wolfbeis, Angew. Chem. Int. Ed. Engl., 38, 1108 (1999).

58. Toshifumi Takeuchi, Daigo Fukuma, and Jun Matsui, “Combinatorial Molecular Imprinting: An Approach to Synthetic Polymer Receptors”, Analytical Chemistry, 71, 285-290 (1999).

59. Francesca Lanza and Borje Sellergren, “Methods for Synthesis and Screening of Large Groups of Molecularly Imprinted Polymers”, Analytical Chemistry, 71, 2092-2096 (1999).

60. Bradley R. Hart, Daniel J. Rush, and Kenneth J. Shea, “Discrimination Between Enantiomres of Structurally Related Molecules: Separation of Benzodiazepines by Molecularly Imprinted Polymers”, J. Am. Chem. Soc., 122, 460-465 (2000).

61. Bradley R. Hart and Kenneth J. Shea, “Synthetic Peptide Receptors: Molecularly Imprinted Polymers for the Recognition of Peptides Using Peptide-Metal Interactions”, J. Am. Chem. Soc., 123, 2072-2073 (2001).

62. Bradley R. Hart and Kenneth J. Shea, “Molecular Imprinting for the Recognition of N-Terminal Histidine Peptides in Aqueous Solution”, Macromolecules, 35, 6192-6201 (2002).

63. Daniel J. Duffy, Kanad Das, Shaw L. Hsu, Jacques Penelle, Vincent M. Rotello and Howard D. Stidham, “Binding Efficiency and Transport Properties of Molecularly Imprinted Polymer Films”, J. Am. Chem. Soc., 124, 8290-8296 (2002).

64. N. Sneshkoff, K. Crabb and J. J. BelBruno, “An Improved Molecularly Imprinted Polymer Film for the Recognition of Amino Acids”, Journal of Applied Polymer Science, 86, 3611-3615 (2002).

65. Mitch K.-P. Leung, Cheuk-Fai Chow and Michael H.-W. Lam, “A sol-gel derived molecular imprinted luminescent PET sensing materials for 2,4-dichlorophenoxyacetic acid”, J. Mater. Chem, 11, 2985-2991 (2001).

66. Linden D. V. Bolisay, John F. March, William E. Bentley and Peter Kofinas, “Separation of baculoviruses using molecularly imprinted polymer hydrogels”, Mat. Res. Soc. Symp. Proc., Volume 787, page G3.1.1-G3.1.5 (2004).

67. Paraskevi Parmpi and Peter. J. Kofinas, “Biomimetic glucose recognition using molecularly imprinted polymer hydrogels”, Biomaterials, 1969-1973 (2003).

68. Toshifumi Takeuchi and Jun Haginaka, “Separation and sensing based on molecular recognition using molecularly imprinted polymers”, Journal of Chromatography B, 728, 1-20 (1999).

69. Sergey A. Piletsky and Anthony P. F. Turner, “Electrochemical Sensors Based on Molecularly Imprinted Polymers”, Electroanalysis, 14, 317-323 (2003).

70. Scott Mcniven and Isao Karube, “Towards optical sensors for biologically active molecules”, Chapter 20 in **Molecularly Imprinted Polymers – Man-made mimics of antibodies and their applications in analytical chemistry, Borje Sellergren editor**, Elsevier, New York (2001).

71. M. C. Blanco-Lopez, M. J. Lobo-Castanon, A. J. Miranda-Ordieres and P. Tunon-Blanco, “Electrochemical sensors based on molecuraly imprinted polymers”, Trends in Analytical Chemistry, 23, 36-48 (2004).

72. Dario Kitz and Richard J. Ansell, Chapter 18 in **Molecularly Imprinted Polymers – Man-made mimics of antibodies and their applications in analytical chemistry, Borje Sellergren editor**, Elsevier, New York (2001).

73. D. Kitz, L. I. Andersson, M. Khayyami, B. Danielson,P.-O. Larsson, and K. Mosbach, Biomimetics, 3, 81 (1995).

74. Peter G. Conrad II, Peter. T. Nishimura, Damian Aherne, Benjamin J. Schwartz, Dong Min Wu, Nicolas Fang, Xiang Zhang, Joseph Roberts, and Kenneth J. Shea, "Functional Molecularly Imprinted Polymer Microstructures Fabricated Using Microstereolithography", Advanced Materials, 15, 1541-1544 (2003).

75. Mark E. Davis, "Ordered porous materials for emerging applications", Nature, 417, 813-821 (2002).

76. http://www.wtec.org/loyola/nano/US.Review/07_03.htm

77. R. A. Dunbar, J. D. Jordan, and F. V. Bright, Analytical Chemistry, 68, 604 (1996).

78. T. A. Dickenson, J. White, J. S. Kauer and D. R. Walt, Nature, 382, 697 (1996).

79. http://topaz.ethz.ch/IZA-SC/XRDpatterns.htm

80. Thomas Bein, "Synthesis and Applications of Molecular Sieve Layers and Membranes", Chem. Mater., 8, 1636-1653 (1996).

81. K. J. Shea and D. A. Loy, "Bridged Polysilsesquioxanes: Molecular Engineering of Hybrid Organic- Inorganic Materials", MRS Bulletin, 368-375, May 2001.

82. D. A. Loy, B. M. Baugher, S. Prabakar, R. A. Assink, and K. J. Shea, in **Advances in Porous Materials (Mater. Res. Soc. Symp. Proc. 371, Pittsburgh, 1995),** edited by Komarneni D. M. Smith and J. S. Beck, page 229.

83. R. M. Shaltout, D. A. Loy, M. D. McClain, S. Prabakar, J. Greaves and K. J. Shea, Polym. Prepr. 508, 41 (2000).

84. D. A. Loy, E. M. Russick, S. A. Yamanaka, B. M. Baugher and K. J. Shea, Chem. Mater., 2264, 9 (1997).

85. Y. Lu, H. Fan, N. Doke, D. A. Loy, R. A. Assink, D. A. LaVan and C. J. Brinker, J. Am. Chem. Soc. 5256, 122 (2000).

86. C. J. Brinker, R. Seghal, S. L. Hietala, R. Deshpande, D. M. Smith, and C. S. Ashley, J. Membr. Sci., 85, 94 (1994).

87. A. Katz and M. E. Lewis, Nature, 6767, 403 (2000).

88. K. J. Shea, D. A. Loy and O. W. Webster, J. Am. Chem. Soc., 6700, 114 (1992).

89. D. A. Loy, G. M. Jamison, B. M. Baugher, E. M. Russick, R. A. Assink, S. Prabakar and K. J. Shea, J. Non-Cryst. Solids, 44, 186 (1995).

90. 90. P. D. E. Biggins, J. Hiltz, A. Kusterbeck, and J. Lewis, “Biotechnological Advances to Materials and Sensing Systems - MAT Group AG13 Final Report”, DOC-MAT-AG13-2006, April 2006.

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Biological sensing systems or biosensors have several characteristics that make them attractive models for military sensing systems. These include specificity, sensitivity, reproducibility, and the ability to detect a wide range of compounds. However, biosensors have limitations. These include sensitivity to extremes of temperature, pressure, or hydrogen ion concentration (pH), and many are incompatible with organic solvents. In some instances, there is a lack of a suitable biosensing material for a particular analyte, while in others cost and time to develop biosensors are excessive.

Biomimetics or bioinspired approaches to sensors or sensor materials development attempt to reproduce the sensitivity and specificity of biosensors while eliminating or reducing some of their limitations. However, the challenges are in producing extremely pure receptors, incorporating them into a sensor, and in increasing the stability of these receptors. In this Technical Memorandum, several bioinspired approaches to the preparation of materials with applications to sensing systems are reviewed and discussed with respect to their strengths and limitations. Specifically, molecularly imprinted polymers (MIPs), synthetic molecular sieves and high surface area, highly porous polymers based on polysilsesquioxanes are reviewed and their applicability to future defence applications discussed.

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